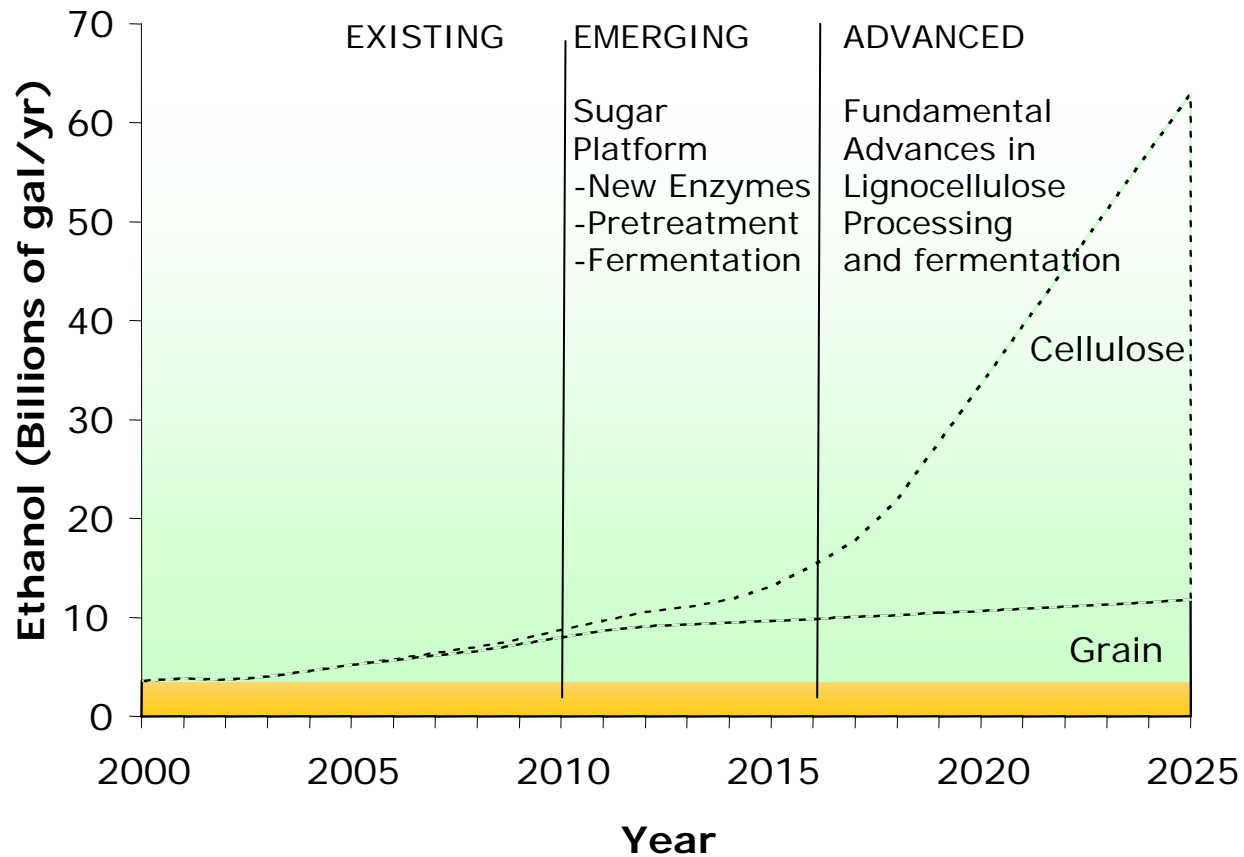


Development of Cellulosic Biofuels

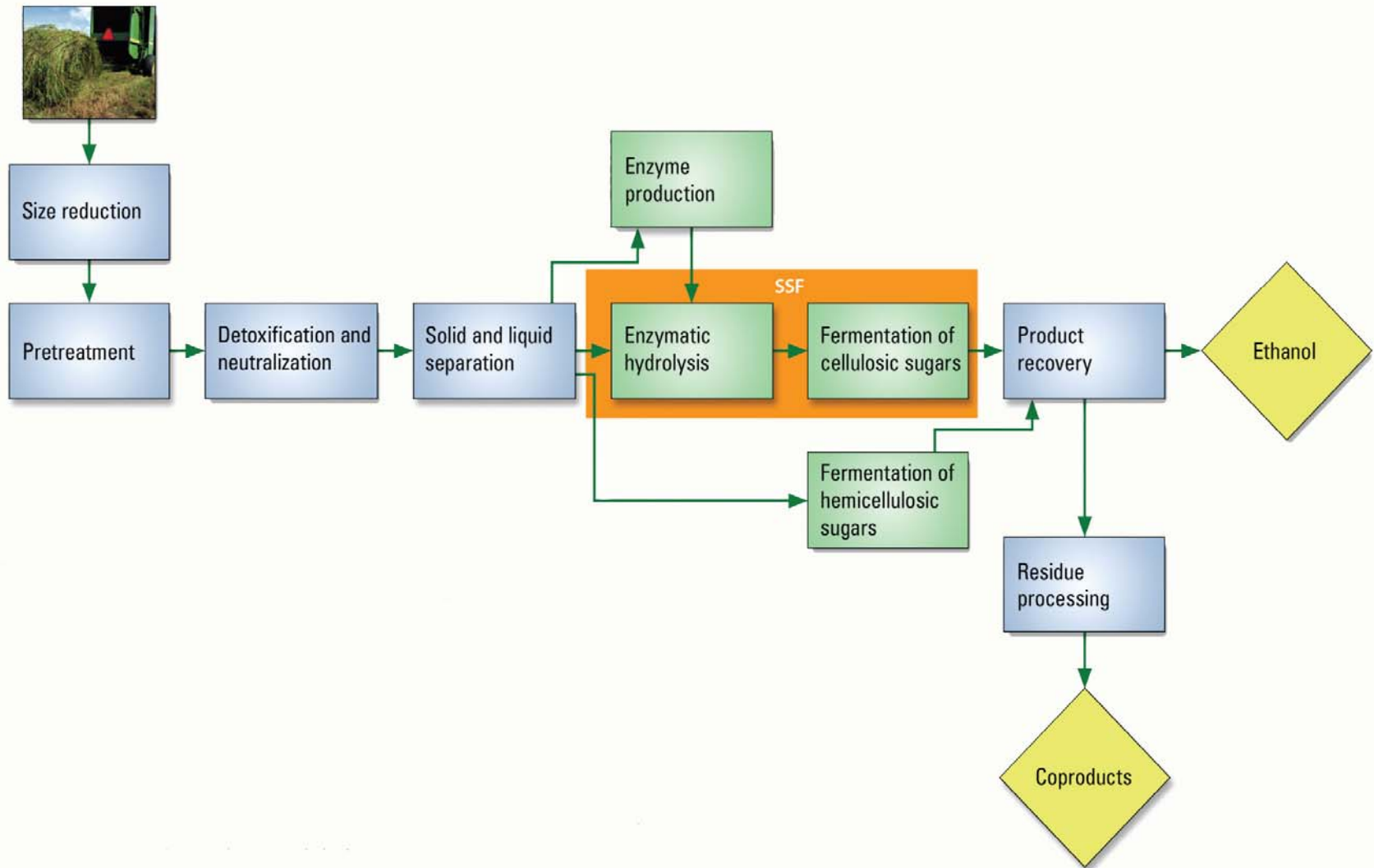


Chris Somerville
Carnegie Institution, Stanford University,
Lawrence Berkeley National Lab

A DOE Ethanol Vision

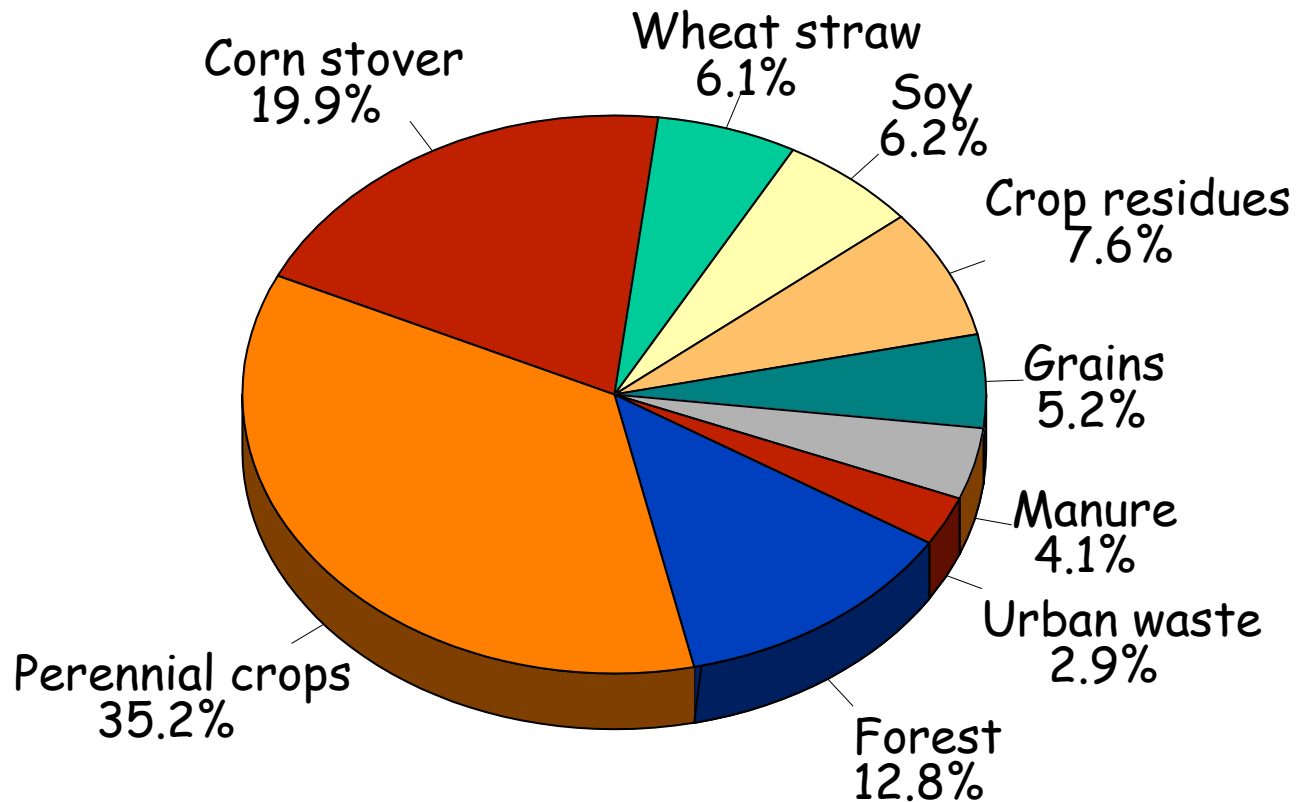


Steps in cellulosic ethanol production



From: Breaking the Biological Barriers to Cellulosic Ethanol

US Biomass inventory = 1.3 billion tons



From: Billion ton Vision, DOE & USDA 2005

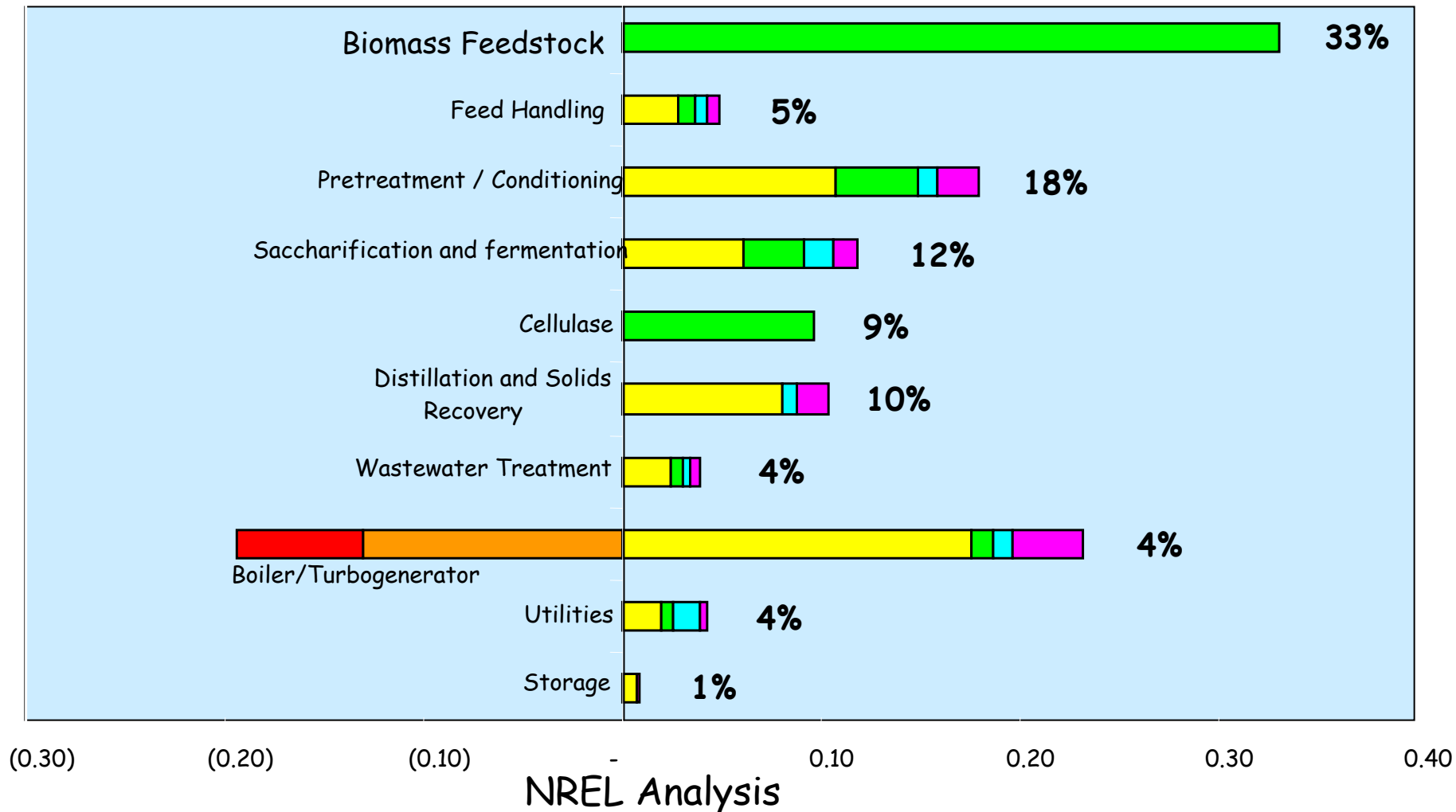
>1% yield is feasible

Yield of 26.5 tons/acre observed by Young & colleagues
in Illinois, without irrigation

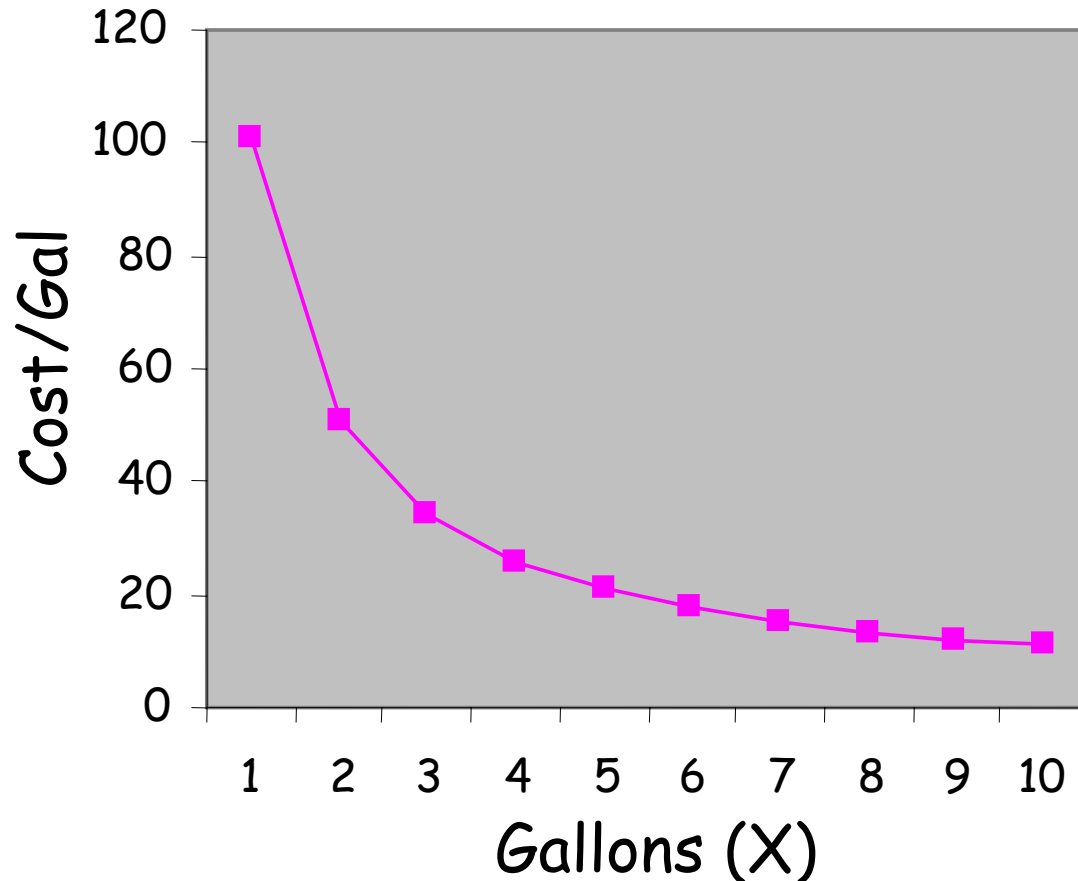
Courtesy of Steve Long et al



Relative cost factors of cellulosic ethanol



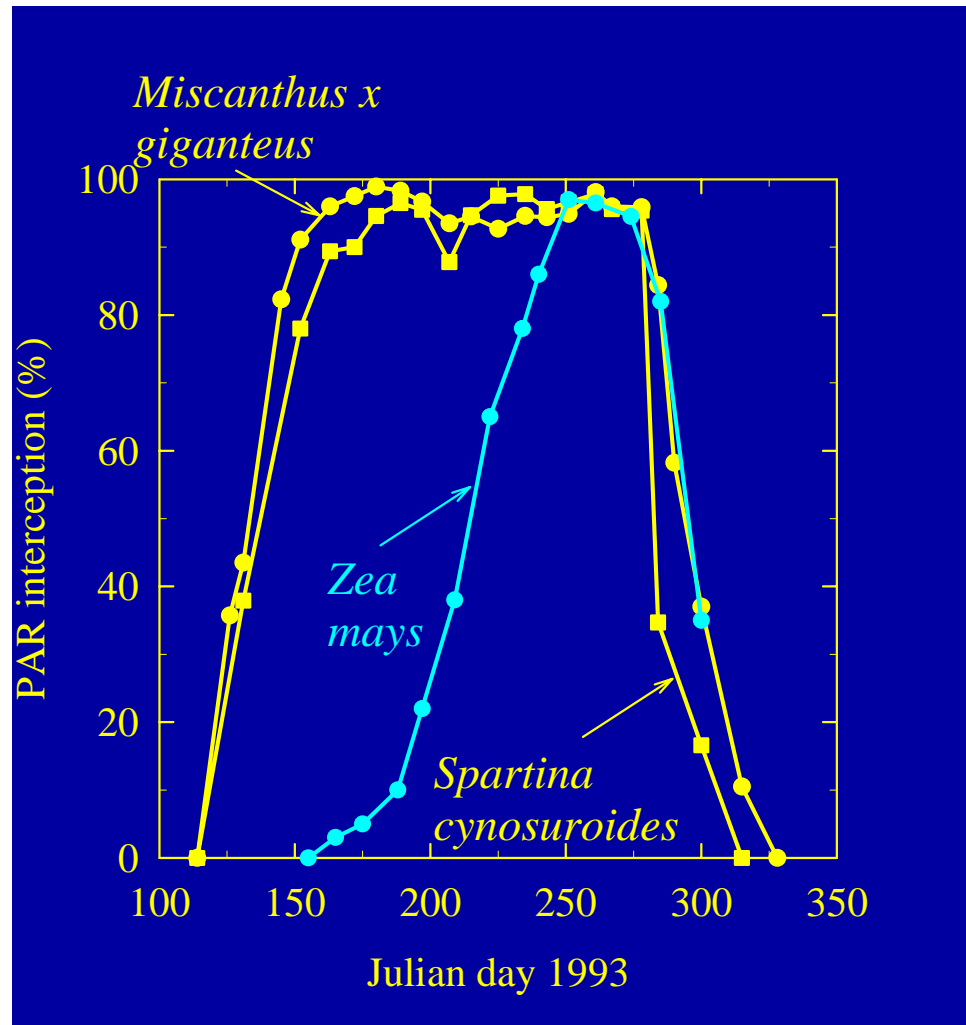
Plot of $\text{Cost/gal} = (Y + aX)/X$



At 15 t/a , $300 \text{ Mgal} \sim 30\%$ of all land in 20 mile radius

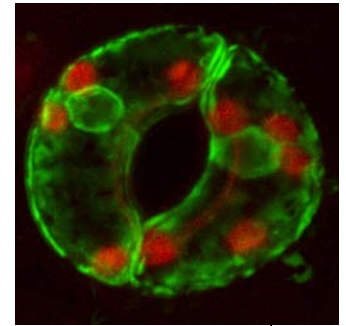
$1 \text{ mi} \times 0.5 \text{ mi} \times 35 \text{ ft}$

Perennials have more photosynthesis



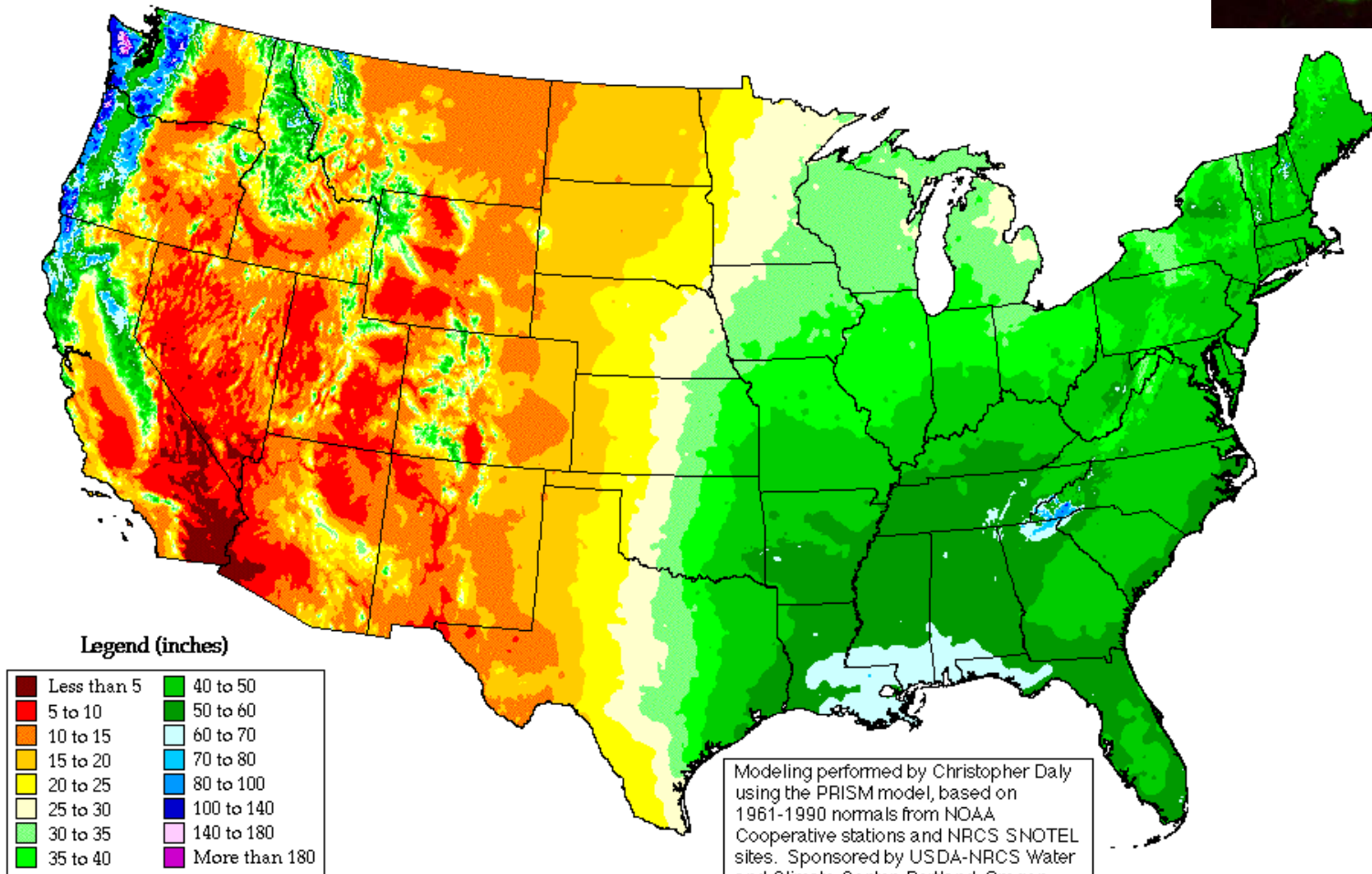
Courtesy of Steve Long, University of Illinois

Annual precipitation



Annual Average Precipitation

United States of America

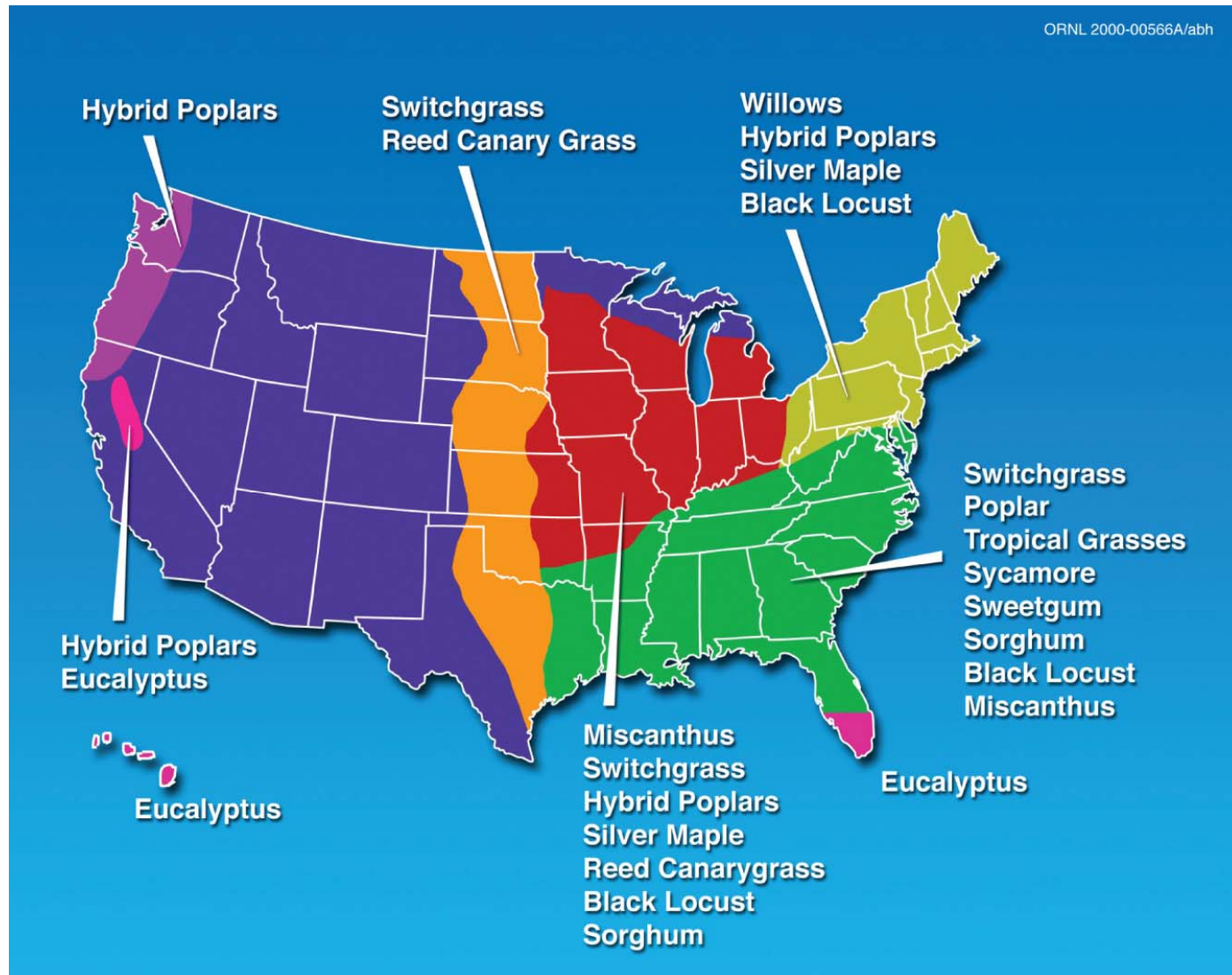


Period: 1961-1990

Modeling performed by Christopher Daly using the PRISM model, based on 1961-1990 normals from NOAA Cooperative stations and NRCS SNOTEL sites. Sponsored by USDA-NRCS Water and Climate Center, Portland, Oregon.

Oregon Climate Service
George Taylor, State Climatologist
(541) 737-5705

Geographic distribution of biomass



Economics of Perennials are Favorable

CROP	Yield per Acre	Value \$ @\$50/t	Cost \$	Profit \$
Corn	160 bu	500	193*	307
Switchgrass	10 tons	500	138**	362
Miscanthus	15 tons	750	193	557

*USDA economic research service 2004

**50% as much fertilizer, no chemicals

Prospective energy crops have not been subject to intensive breeding



Miscanthus sp.



Switchgrass (*Panicum virgatum*)

Courtesy of Steve Long & Emily Heaton. USDA-NRCS PLANTS Database / Hitchcock, A.S. (rev. A. Chase). 1950. *Manual of the grasses of the United States*. USDA Misc. Publ. No. 200. Washington, DC.

Advantages of perennials

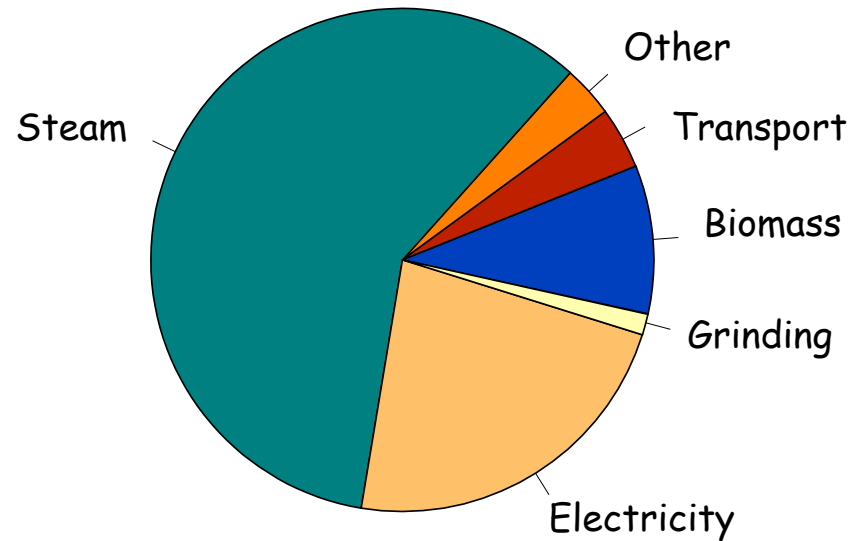
- Energy crops are expected to be more environmentally benign than production agriculture
 - Low fertilizer and chemical inputs
 - Late-harvest supports biodiversity
 - Mixed cultures possible
 - Many species can be used

Challenges in developing energy crops

- Self-incompatibility creates challenges in breeding
- Difficult to capture adequate value from seed production
- Large capital costs in building cellulosic ethanol plants will require long-term contracts

The challenge is efficient conversion

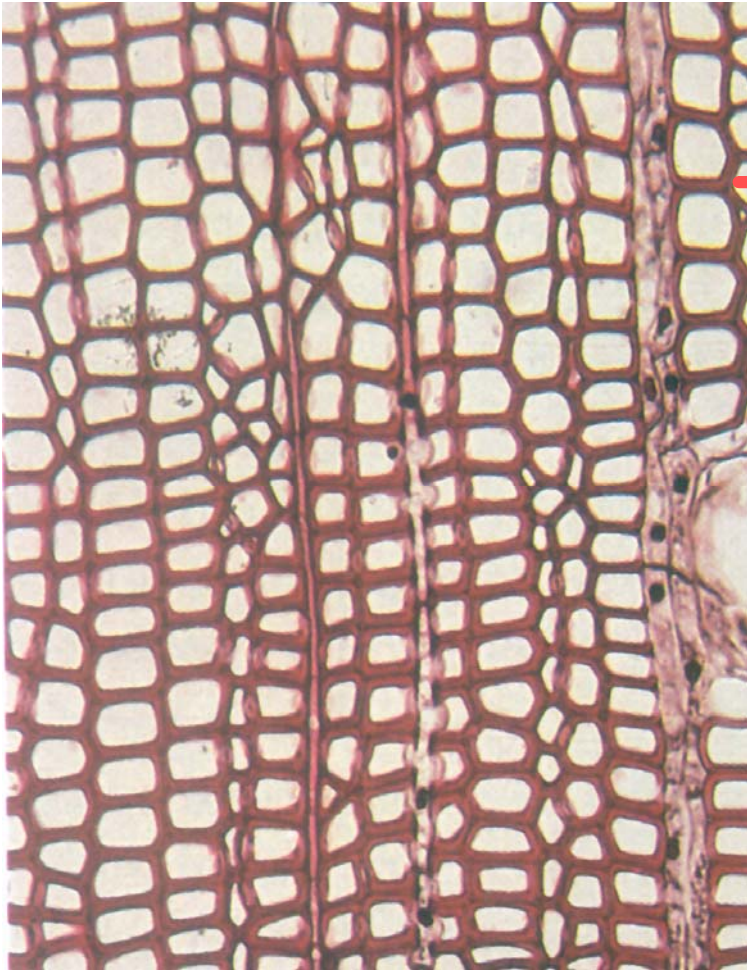
- Burning switchgrass (10 t/ha) yields 14.6-fold more energy than input to produce*
- But, converting switchgrass to ethanol calculated to consume 45% more energy than produced



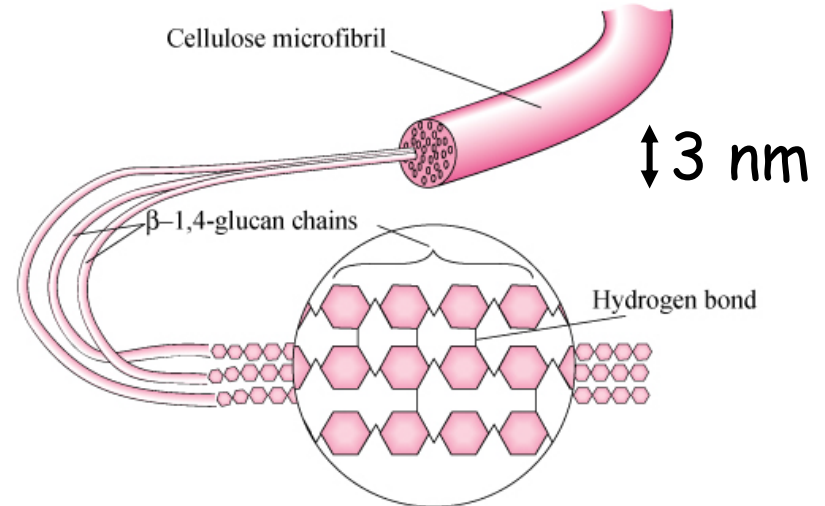
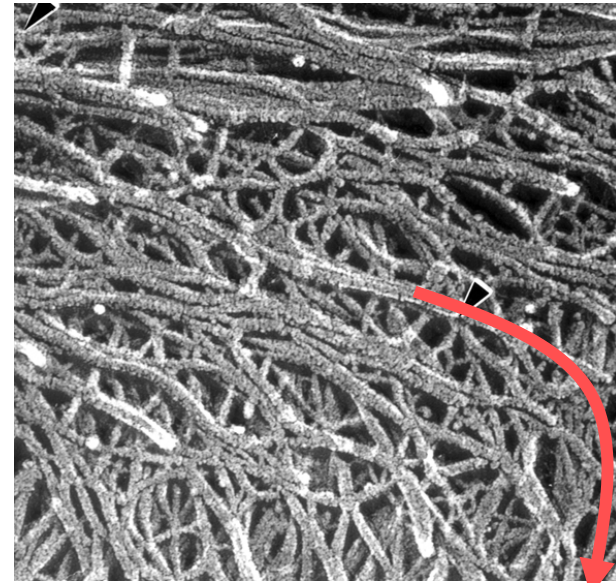
Energy consumption

*Pimentel & Patzek, Nat Res Res 14,65 (2005)

Plants are mostly composed of sugars

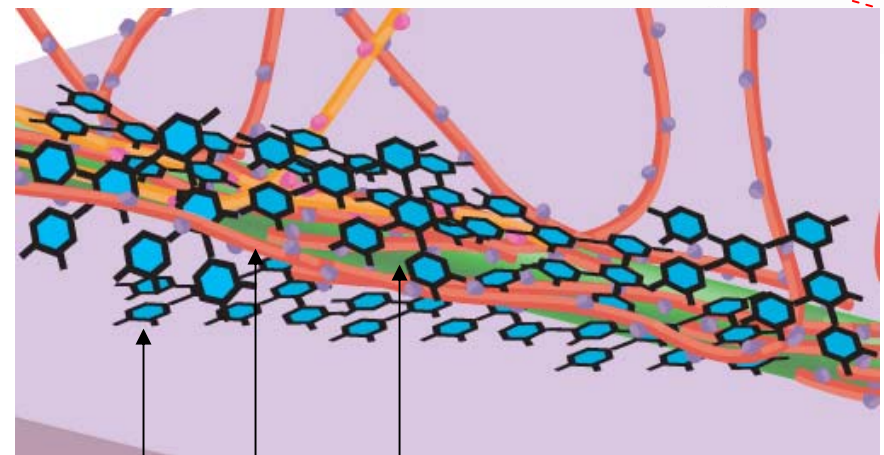
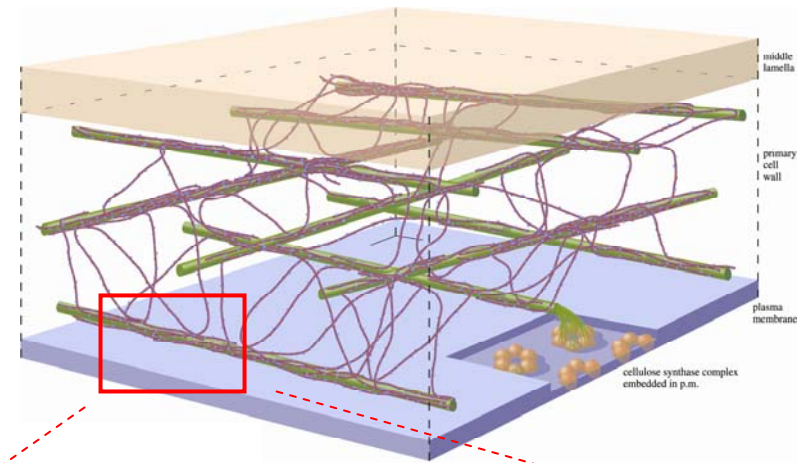
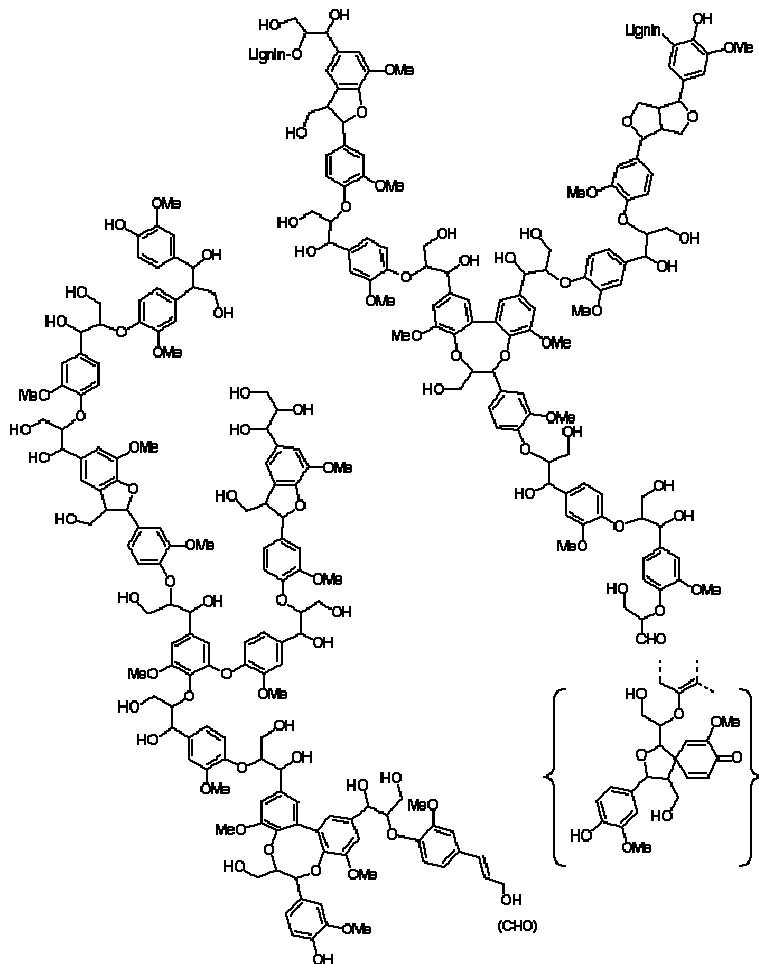


Section of a pine board



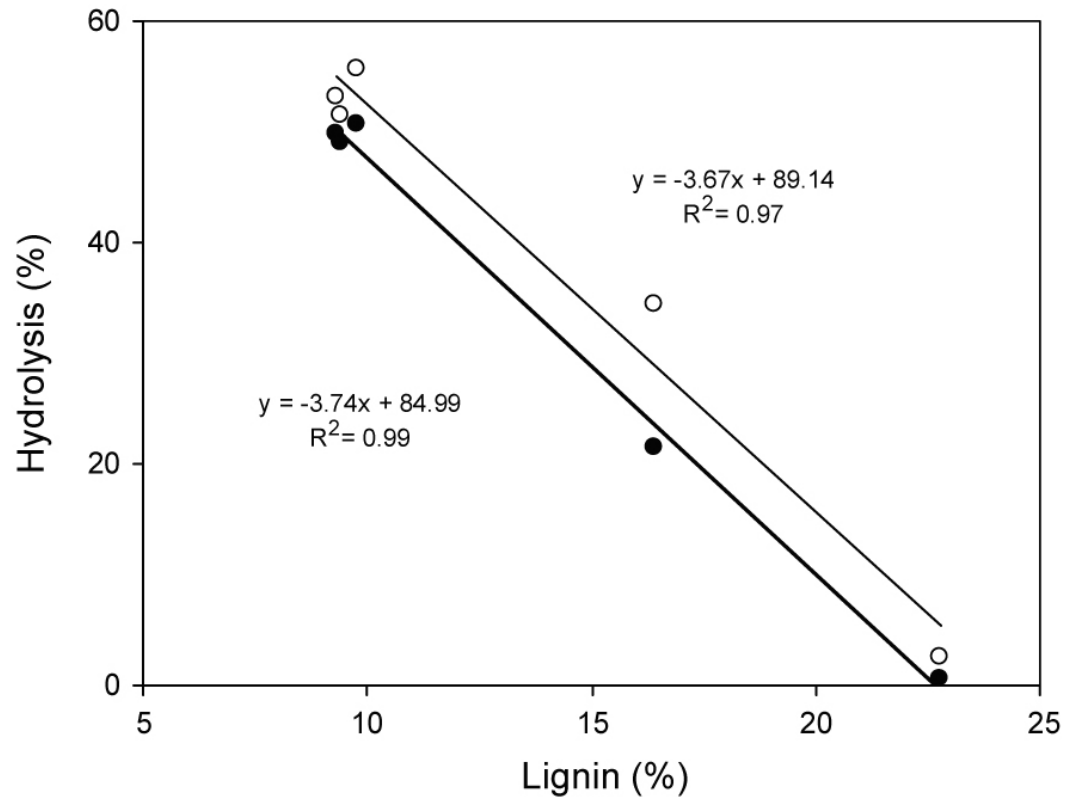
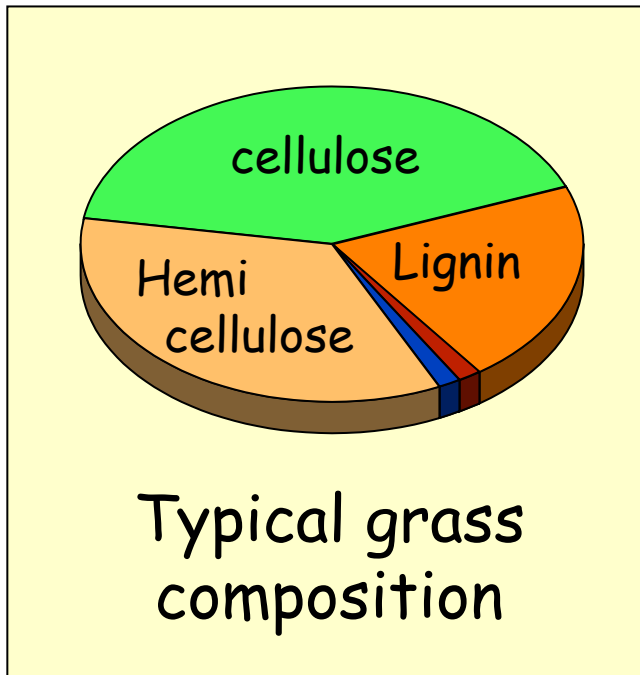
Polymerized glucose

Lignin occludes polysaccharides



Lignin
Hemicellulose
Cellulose

Effect of lignin content on enzymatic recovery of sugars from Miscanthus



Lignin biosynthesis

The diagram illustrates the biosynthetic pathways leading to different types of lignin units:

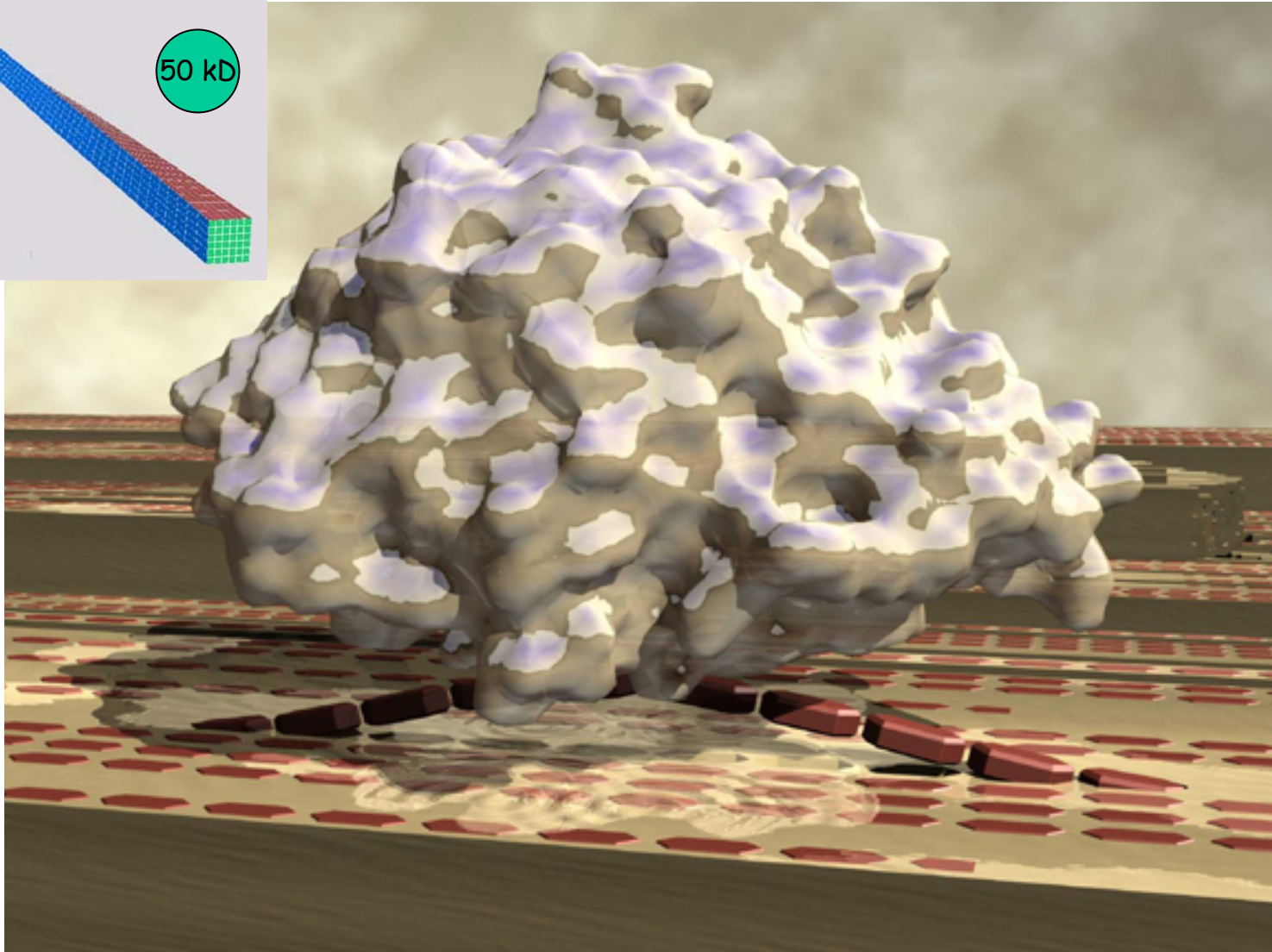
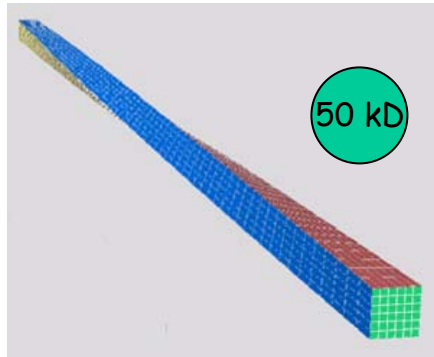
- p-Hydroxyphenyl lignin:** Derived from Phenylalanine via Cinnamic acid and p-Coumaric acid. It can form p-Coumaraldehyde (via CAD?) or p-Coumaryl alcohol.
- Guaiacyl lignin:** Derived from p-Coumaric acid via Caffeic acid and Ferulic acid. It can form Coniferyl aldehyde (via CAD/SAD) or Coniferyl alcohol.
- Syringyl lignin:** Derived from Ferulic acid via 5-Hydroxyferulic acid and Sinapic acid. It can form Sinapaldehyde (via SAD/CAD) or Sinapyl alcohol.

A central mechanism shows the polymerization of these units through ester linkages involving shikimic acid or quinic acid derivatives, catalyzed by enzymes like CST or CQT, followed by release by C3H. This leads to the formation of complex polymeric structures like caffeoyl shikimic acid, which can further be modified by C3H to form caffeoyl quinic acid. These intermediates are then converted back to their respective CoA esters (Caffeoyl CoA, Feruloyl CoA, Sinapoyl CoA) by CCoAOMT.

Enzymes involved include PAL, 4CL, COMT, F5H, CCR, CAD, and SAD/CAD.

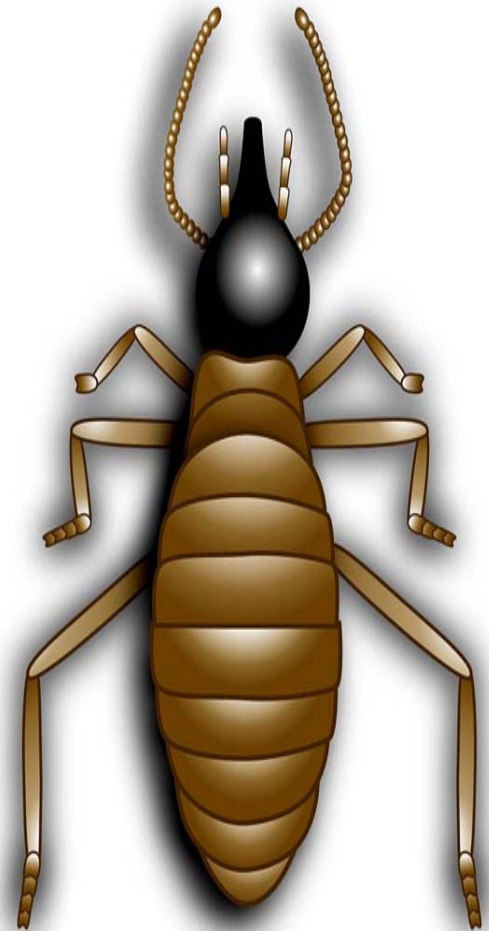
Current Opinion in Plant Biology

Cellulose is recalcitrant to hydrolysis

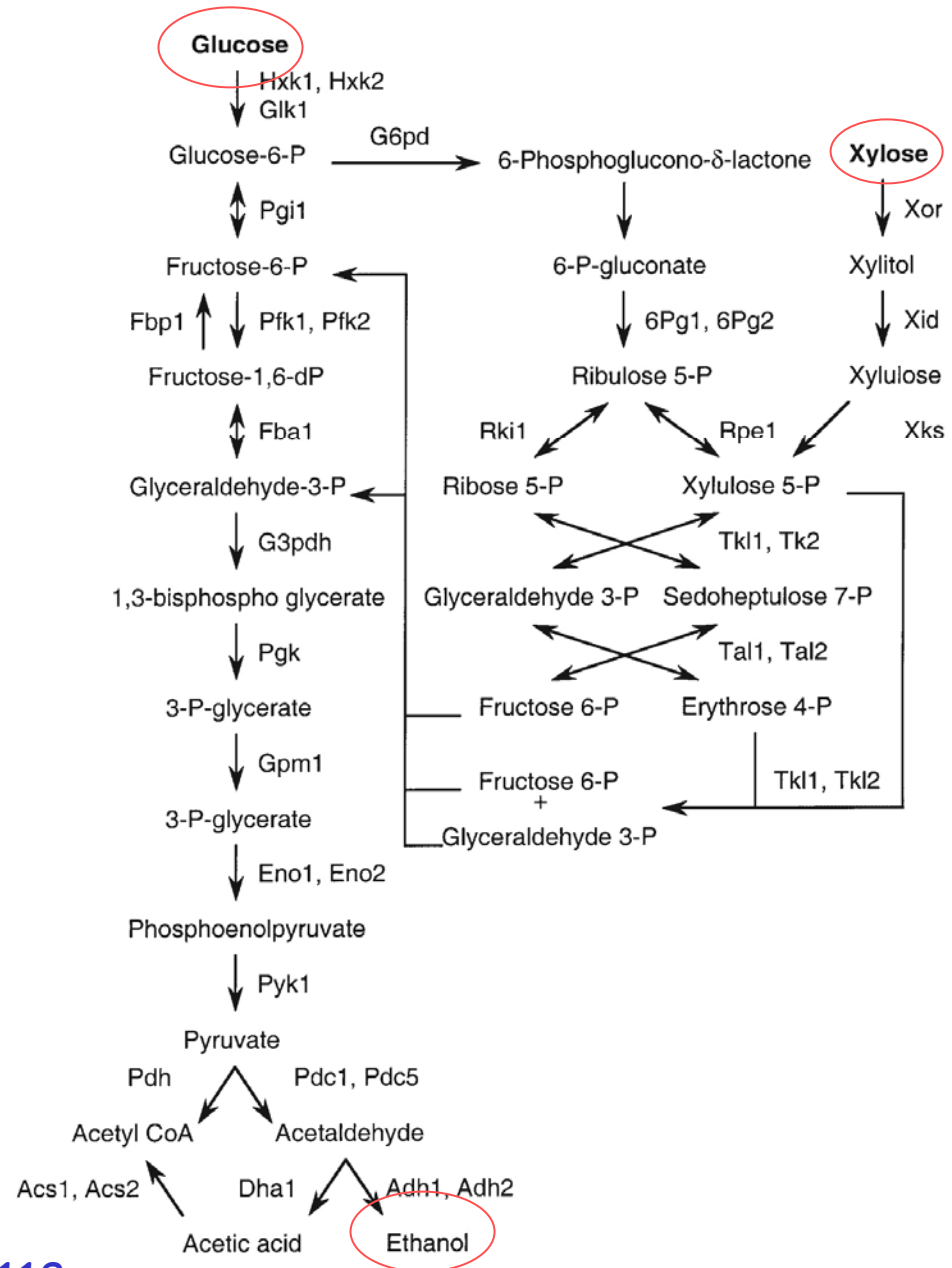
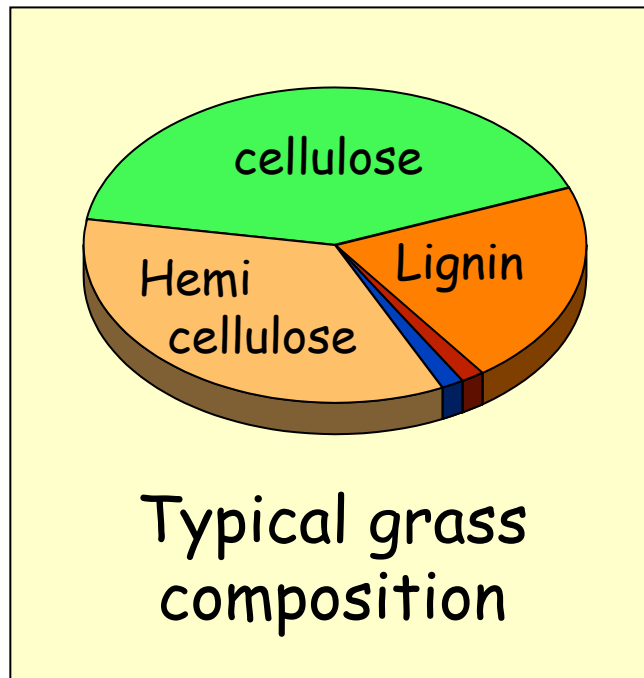


Possible routes to improved catalysts

- Explore the enzyme systems used by termites (and ruminants) for digesting lignocellulosic material
- Compost heaps and forest floors are poorly explored
- In vitro protein engineering of promising enzymes
- Develop synthetic organic catalysts (for polysaccharides and lignin)



Fermentation of all sugars is essential

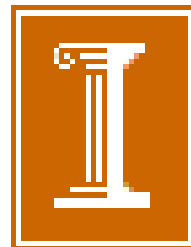


Conclusions

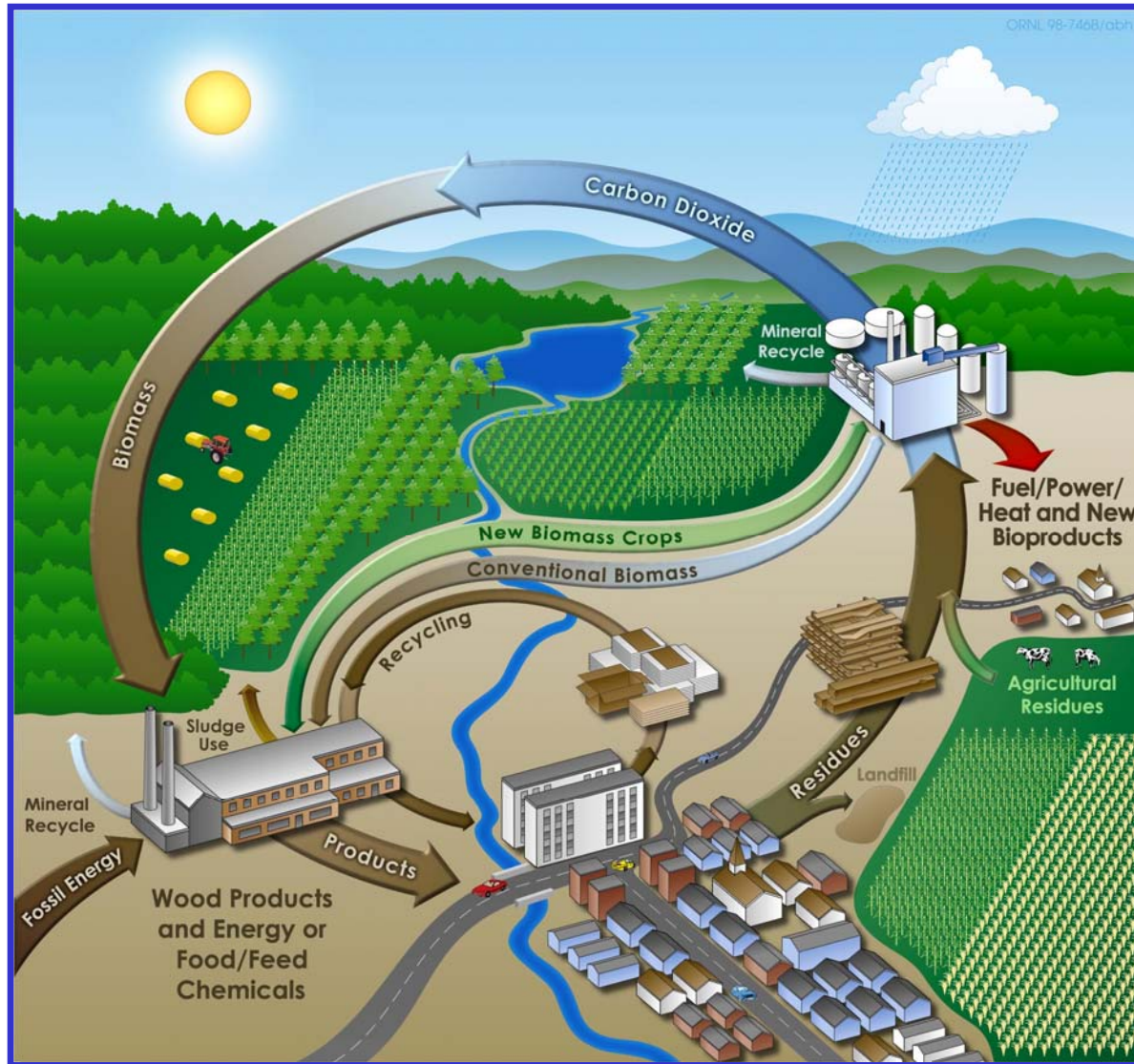
- Biofuels are expected to be an important part of a carbon neutral energy economy
- There are no insurmountable problems
- Many improvements are possible
- The revolution in mechanistic biology offers enormous untapped potential to make fundamental changes in solar harvesting with plants

The Energy Bioscience Institute

- Partnership between UCB, UI, LBL
- BP has committed \$500M over 10 years
- Goals include elimination of bottlenecks to biofuels, development of improved biotechnologies for fuel production, and education of scientists and engineers across the relevant disciplines

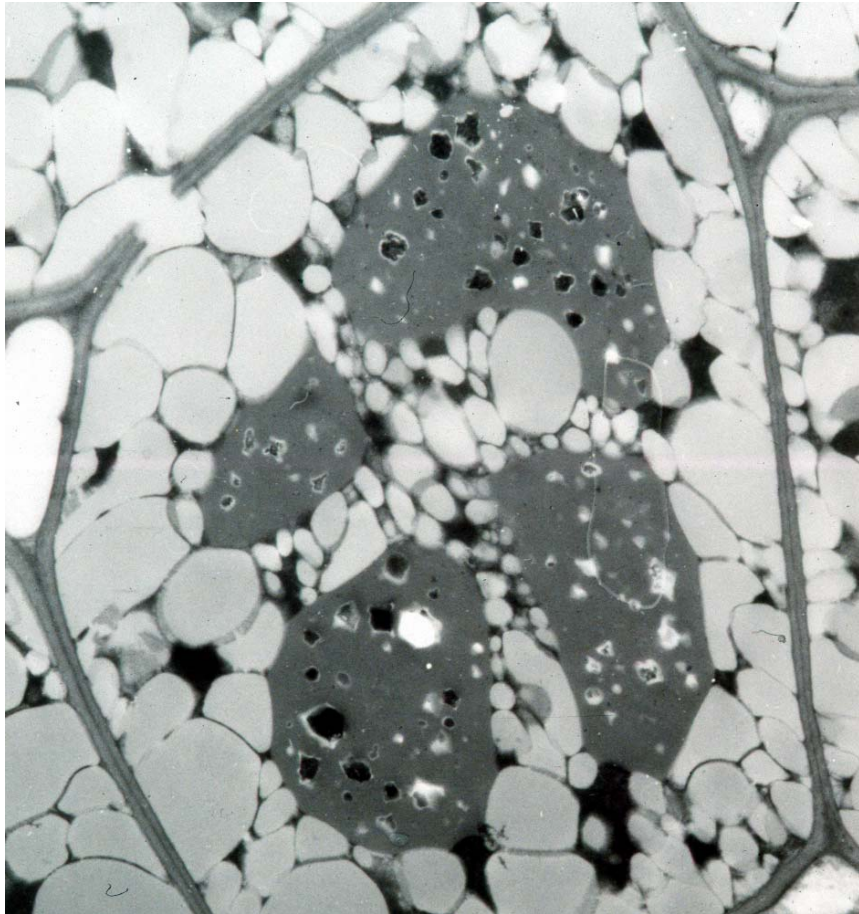


A vision of the Future

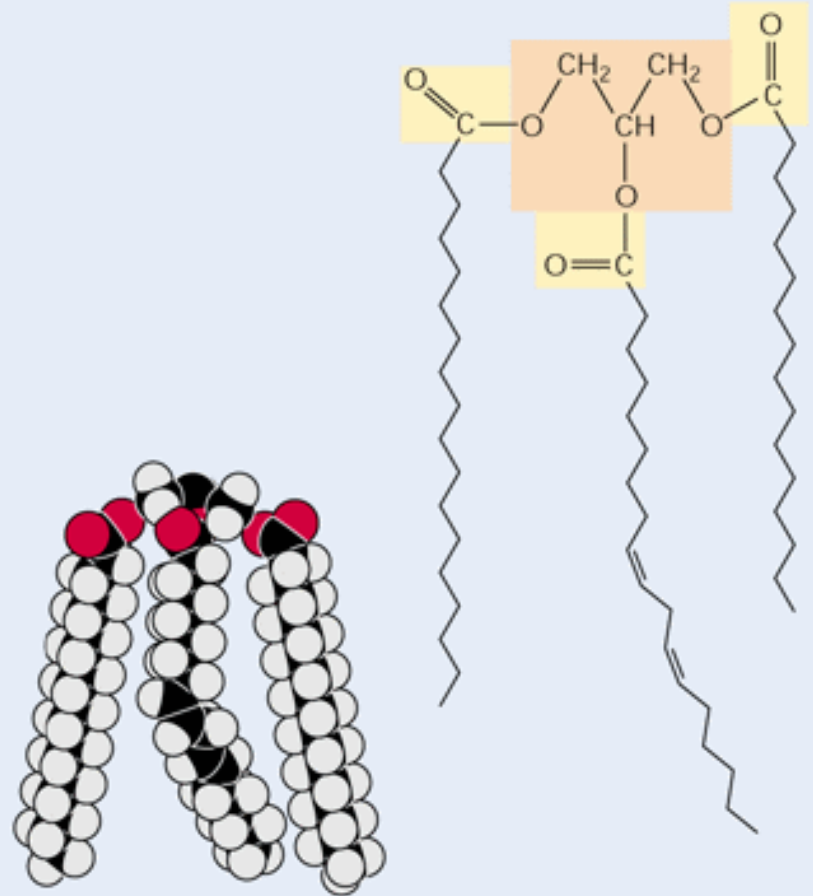


<http://genomicsgtl.energy.gov/biofuels/index.shtml>

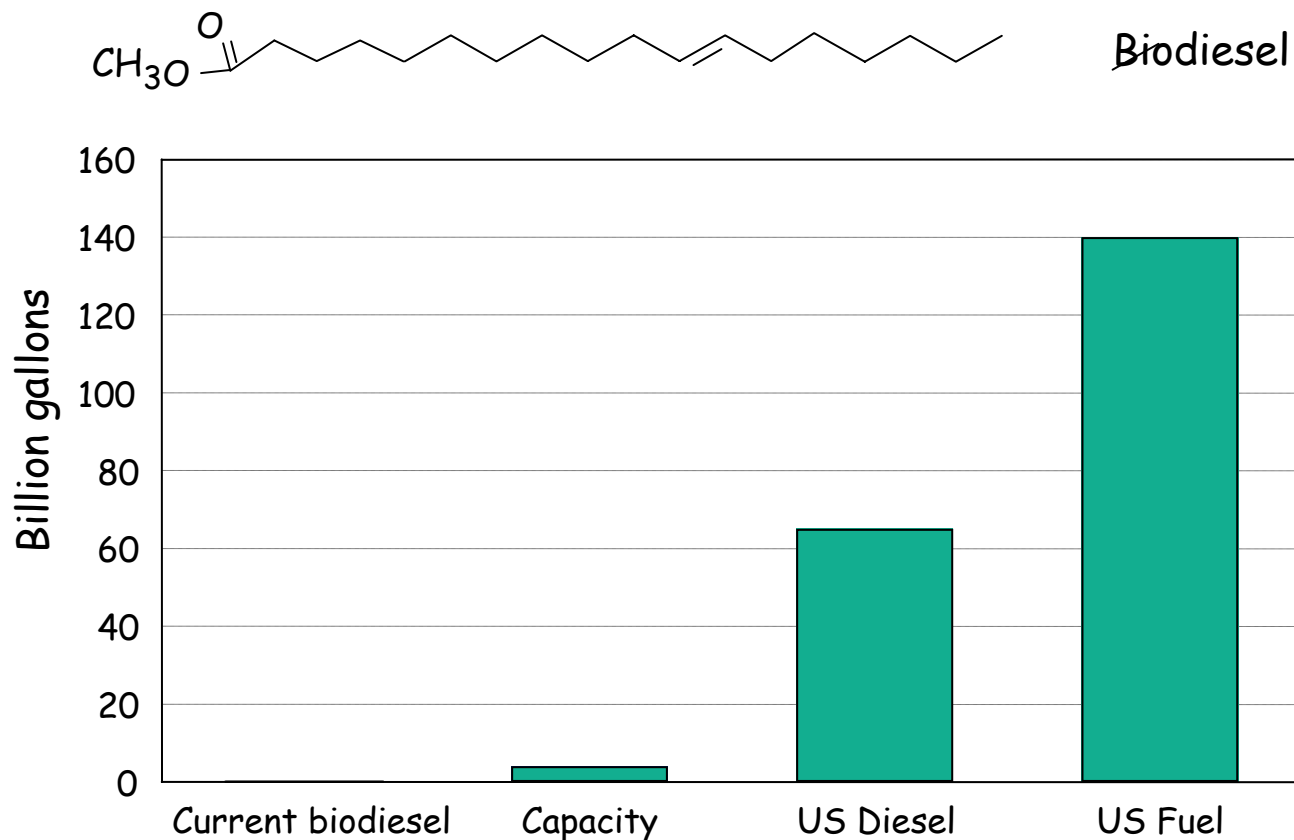
Some plants accumulate oil



(B) Triacylglycerol



Limited potential of biodiesel



65 biodiesel companies in operation, 50 in construction 2006